Beyond the Standard Model: from the Tevatron to the LHC

Fermilab September 2008

$B_s-\overline{B}_s$ mixing and grand unification

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1. GUTs and supersymmetry

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1. GUTs and supersymmetry

The Standard Model has a severe fine-tuning problem... the hypercharge

$$Q = T_3 + Y$$

electric charge | three-component of the weak isospin | hypercharge

right-handed fermions:	$T_3 = 0$
left-handed up-type fermions:	$T_3 = 1/2$
left-handed down-type fermions:	$T_3 = -1/2$

$U(1)_Y$: The normalizations of $U(1)$ couplings and charges are arbitrary.

Y and therefore Q of any fermion could be any real number: π, $\sqrt{2}$, 1.602, ...

But: E.g. $Q(\nu) = 0$, $Q(e) = 3Q(d)$ and $Q(u) = -2Q(d)$ to all digits behind the decimal point, so that neutrinos and atoms are electrically neutral.

Grand unified theories (GUTs)

Grand Unified theories embed $SU(3) \times SU(2) \times U(1)_Y$ into a simple group and thereby fix the Y quantum numbers.

$$SU(3) \times SU(2) \times U(1)_Y \subset SU(5)$$

The fermions nicely fit into $SU(5)$ multiplets:

$$\underline{5} \equiv \begin{pmatrix} d^c \\ d^c \\ d^c \\ e_L \\ -\nu_{e,L} \end{pmatrix} \qquad \underline{10} \equiv \begin{pmatrix} 0 & u^c & -u^c & u_L & d_L \\ -u^c & 0 & u^c & u_L & d_L \\ u^c & -u^c & 0 & u_L & d_L \\ -u_L & -u_L & -u_L & 0 & e^c \\ -d_L & -d_L & -d_L & -e^c & 0 \end{pmatrix}$$

Here the fields with superscript c denote the fields of the antiparticles of the right–handed fermions.

That this works is highly non–trivial: it requires that

- there are 15 chiral fields per generation,
- the hypercharges sum to zero separately for the $\underline{5}$ and the $\underline{10}$,
- two of the four $SU(3)$ triplets are $SU(2)$ singlets and the other two combine to $SU(2)$ doublets,
- the remaining three colourless fields form a singlet and a doublet with respect to $SU(2)$.

Even better: The 15 fermion fields of each Standard Model generation and an extra right-handed neutrino field fit into a $\underline{16}$ of

$$SO(10) \supset SU(5)$$

The light neutrino masses come out with (almost) the right size through the see–saw formula.

Supersymmetry

Hierarchy problem: GUTs contain particles, which are heavier than those of the Standard Model by 14 orders of magnitude. Their quantum effects destabilize the Higgs mass.

Superpartners (fermions $\leftrightarrow$ bosons) with masses below 1 TeV tame the quantum corrections to the Higgs mass.

Supersymmetric theories can explain dark matter through the lightest supersymmetric particle (LSP) and provide attractive mechanisms for baryogenesis.

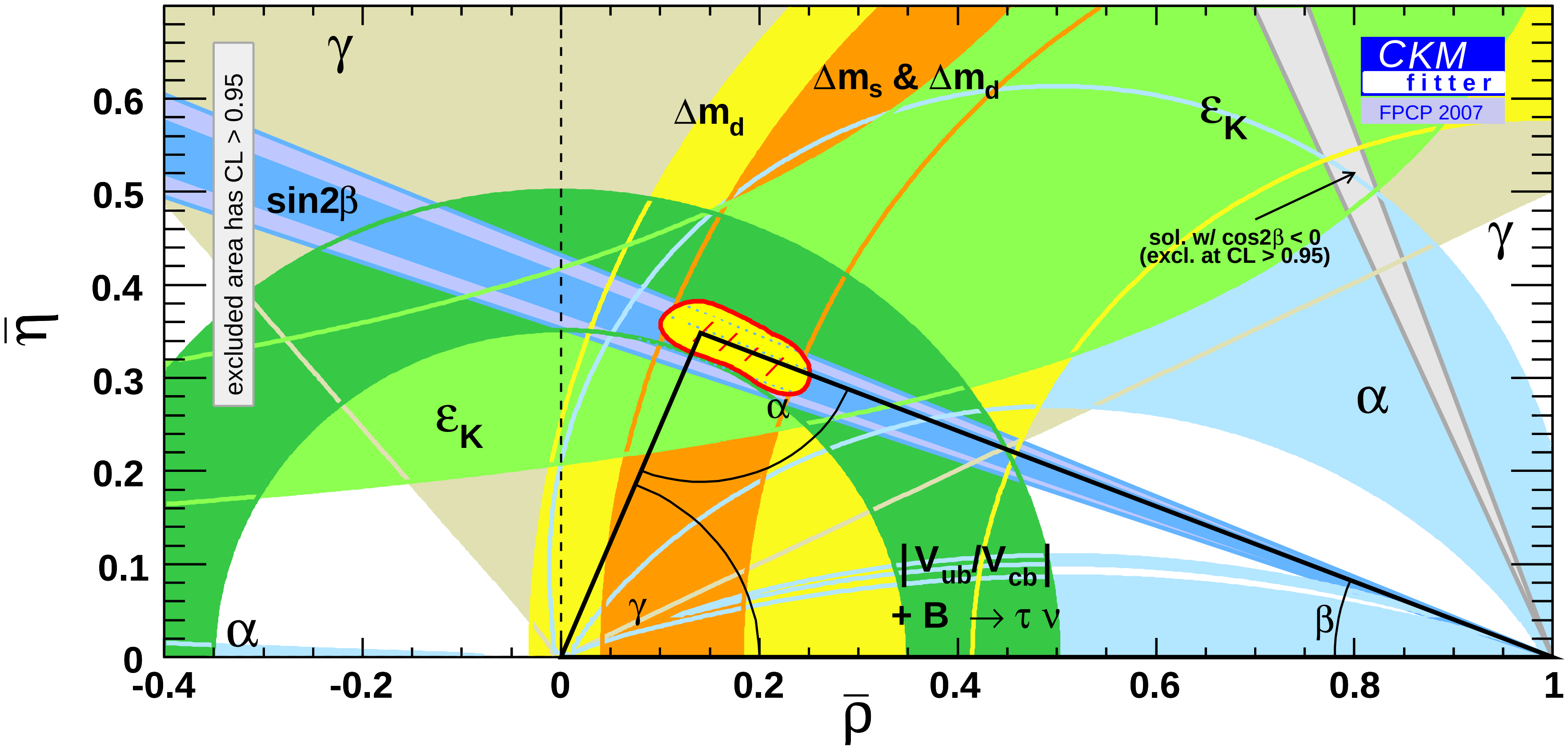
The unification of gauge couplings required by GUTs is improved.

The proton lifetime predicted from GUTs is reconciled with experimental bounds.

Supersymmetric theories can embed gravity.

2. B physics

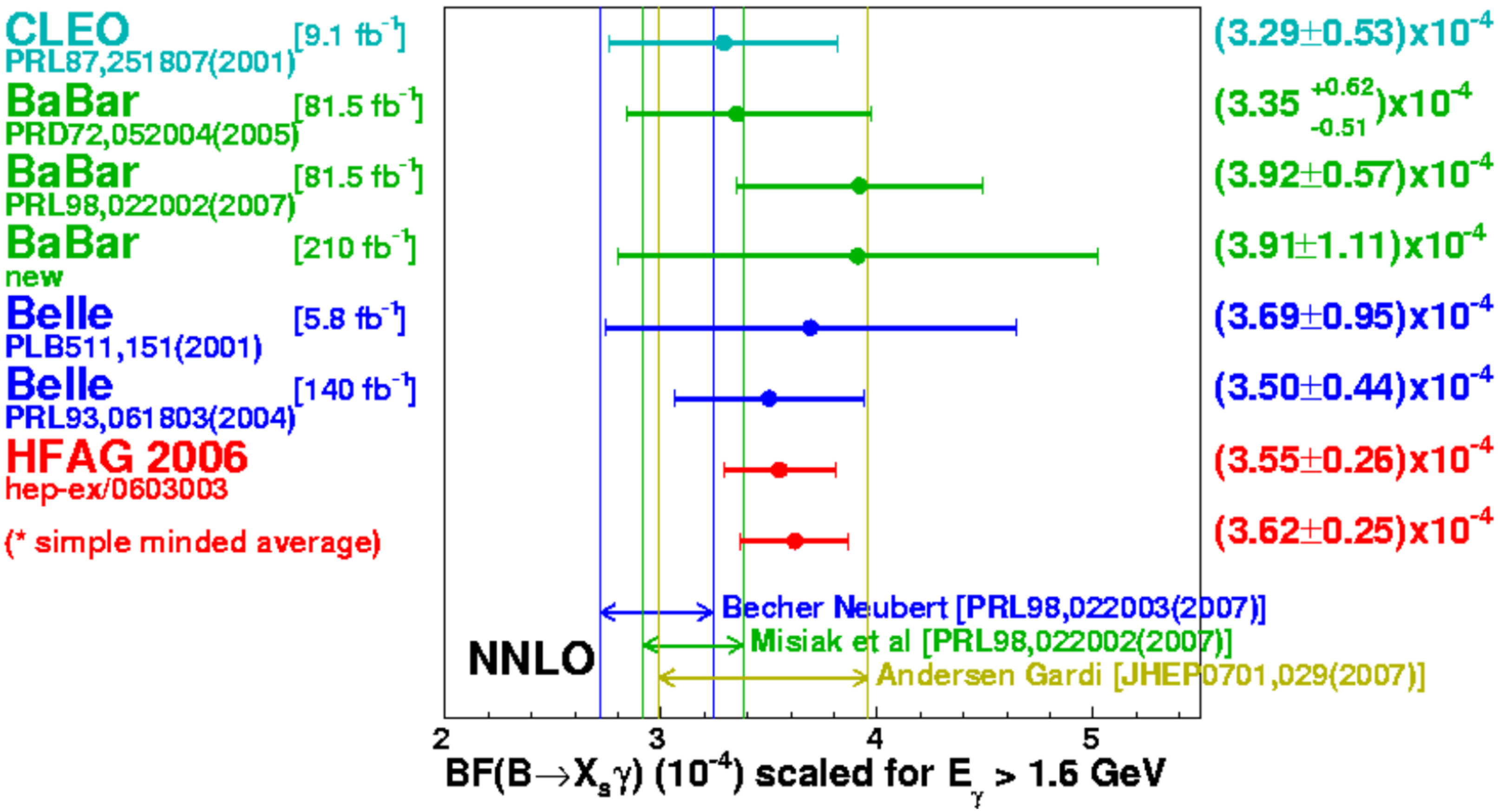
Experimental status of the unitarity triangle



consistent with the Standard Model

CKM mechanism excellently confirmed.

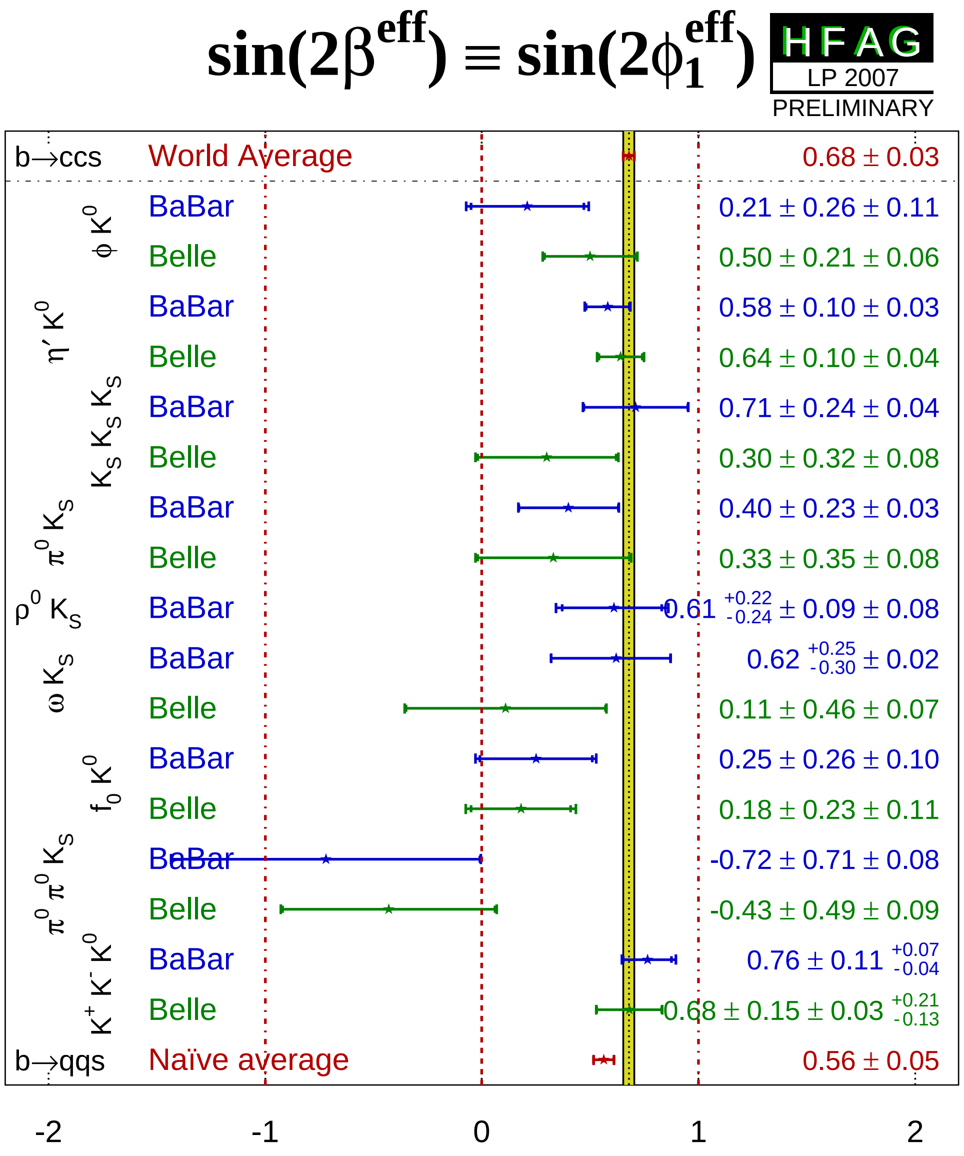
Experimental status of $b \to s\gamma$



consistent with the Standard Model prediction within $\sim 1.5\sigma$:

$$\mathcal{B}(B \to X_s\gamma) \; = \; (2.98 \pm 0.26) \cdot 10^{-4}$$ Becher,Neubert 2006

Experimental status of CP asymmetries in $b \to s$ transitions



Naive average disagrees from the Standard Model expectation by 2.2σ.

Better criterion: absolute deviation from the Standard Model.

	Physics probed:
Unitarity Triangle:	$b \to d$, $s \to d$, $b \to u$
$B \to X_s \gamma$:	$b_R \to s_L$
$C\!\!\not{P}$ in $b \to s$ transitions:	$b \to s$

$\Rightarrow$ Yukawa sector is the dominant source of flavor violation.

The CKM picture works too well:

Flavor problem of TeV scale physics

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Flavor problem of TeV scale physics

In the Minimal Supersymmetric Standard Model (MSSM) all potential new sources of flavor violation come from the SUSY breaking sector. The success of the flavor physics programs at the B factories and the Tevatron severely constrains the associated parameters in the squark mass matrices.

Tev–scale new physics is dominantly minimally flavour–violating (MFV).

$\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing and new physics

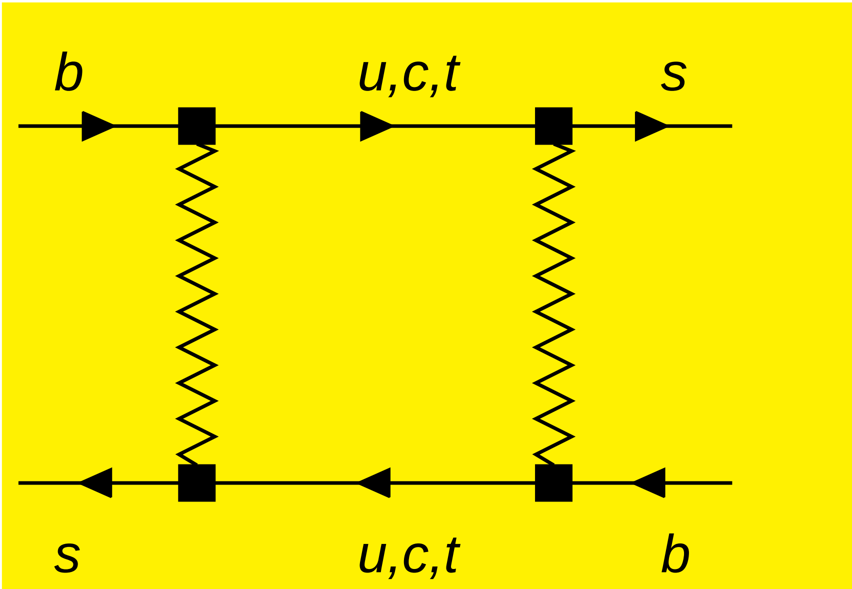
New physics can change magnitude and phase of the transition matrix element

$$M_{12}^s = \frac{\langle B_s | H^{|\Delta B=2|} | \overline{B}_s \rangle}{2 M_{B_s}}$$

Standard Model:

M_{12}^s from dispersive part of box, only internal t relevant.

CP asymmetries are small, below the Tevatron sensitivity.



To identify or constrain new physics one wants to measure both the magnitude and phase of M_{12}^s.

Quantify generic new physics with a complex parameter Δ_s through

$$M_{12}^s \equiv M_{12}^{\mathrm{SM,s}} \cdot \Delta_s \,, \qquad \Delta_s \equiv |\Delta_s| e^{i\phi_s^\Delta} .$$

In the Standard Model $\Delta_s = 1$. Frequently used alternative notation:

$$\Delta_s = r_{\mathrm{s}}^2 \cdot e^{i\,2\theta_s}$$

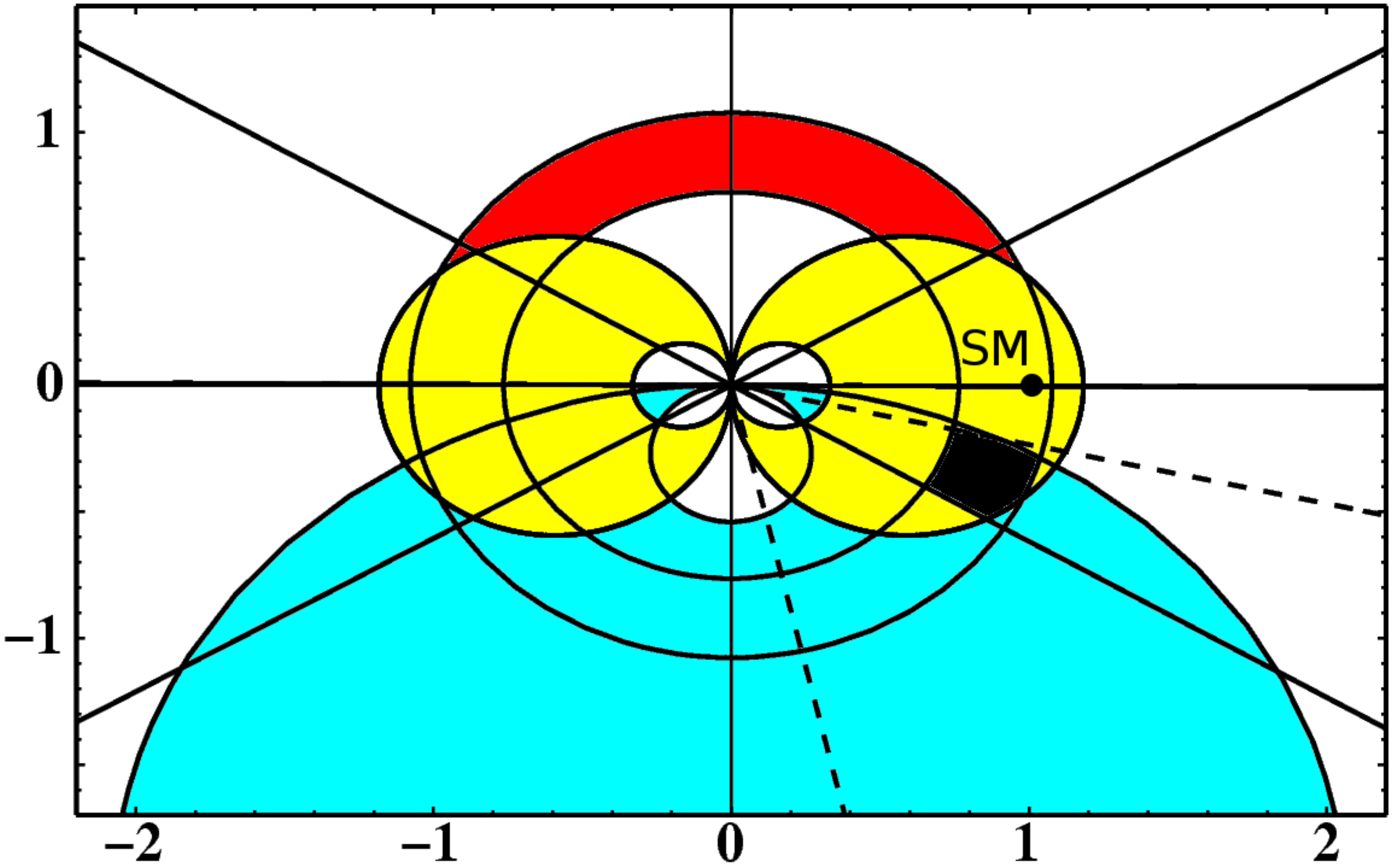
Status of December 2006: CDF or DØ data available for

- the mass difference $\Delta m_s \propto |\Delta_s|$,
- the semileptonic CP asymmetry $a_{\rm fs}^s \propto \sin\phi_s^\Delta$,
- the untagged angular distribution in $\overset{(-)}{B}_s \to J/\psi\phi$, which is sensitive to $\sin\phi_s^\Delta$ and
- the width difference $|\Delta\Gamma_s| \propto |\cos\phi_s^\Delta|$.

Winter 2007/2008: Tagged Measurement of the gold-plated

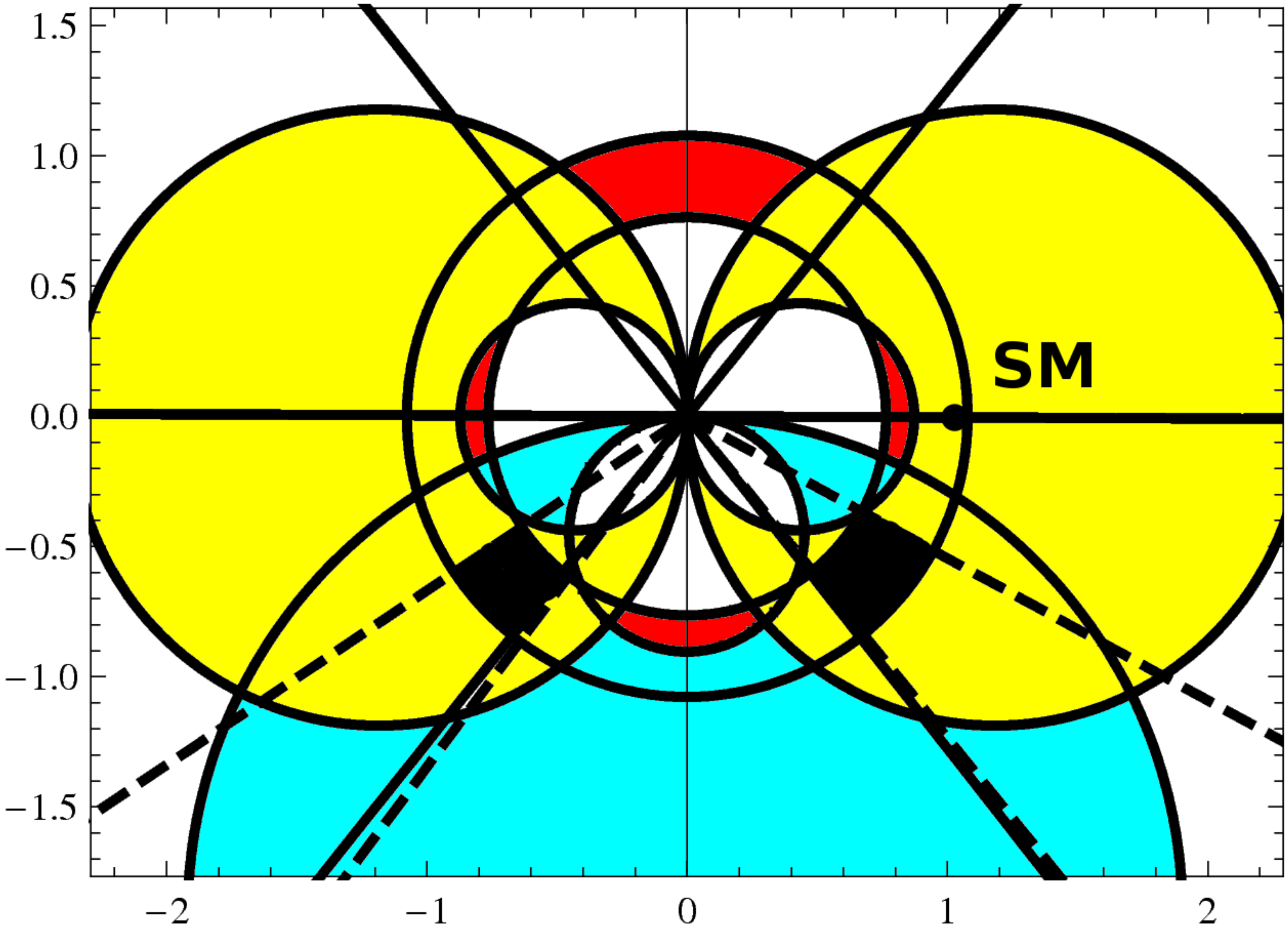
mixing-induced CP asymmetry $\qquad a_{\rm mix}^{\rm CP}(B_s \to J/\psi\phi) \propto \sin\phi_s^\Delta$
(with angular analysis) by CDF and DØ.

The complex Δ_s plane in 2006:



We black area shown corresponds to a deviation from the Standard Model by 2σ. The area delimited by the dashed lines has mirror solutions in the other three quadrants. Alex Lenz, UN

Spring 2008: Adding the results from the tagged CDF and DØ analyses (and updating $a^s_{\rm fs}$):



3. Linking quarks to leptons

Flavour mixing:

quarks: Cabibbo-Kobayashi-Maskawa (CKM) matrix

leptons: Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

Consider SU(5) multiplets:

$$\overline{\mathbf{5}}_{\mathbf{1}} = \begin{pmatrix} d_R^c \\ d_R^c \\ d_R^c \\ e_L \\ -\nu_e \end{pmatrix}, \qquad \overline{\mathbf{5}}_{\mathbf{2}} = \begin{pmatrix} s_R^c \\ s_R^c \\ s_R^c \\ \mu_L \\ -\nu_\mu \end{pmatrix}, \qquad \overline{\mathbf{5}}_{\mathbf{3}} = \begin{pmatrix} b_R^c \\ b_R^c \\ b_R^c \\ \tau_L \\ -\nu_\tau \end{pmatrix}.$$

If the observed large atmospheric neutrino mixing angle stems from a rotation of $\overline{\mathbf{5}}_{\mathbf{2}}$ and $\overline{\mathbf{5}}_{\mathbf{3}}$, it will induce a large $\tilde{b}_R - \tilde{s}_R$-mixing (Moroi).

$\Rightarrow$ new $b_R - s_R$ transitions from gluino–squark loops

The Chang–Masiero–Murayama (CMM) model is based on the symmetry breaking chain

SO(10)$\rightarrow$ SU(5) $\rightarrow$ SU(3)$\times$SU(2)$_L\times$U(1)$_Y$. Chang, Masiero and Murayama

1. The SUSY-breaking terms are universal at the Planck scale.

2. Renormalization effects from the top-Yukawa coupling destroy the universality at $M_{\rm GUT}$.

3. Rotating $\overline{\mathbf{5}}_{\mathbf{2}}$ and $\overline{\mathbf{5}}_{\mathbf{3}}$ into mass eigenstates generates a $\tilde{b}_R - \tilde{s}_R$ element in the mass matrix of right-handed squarks.

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Phenomenological effect: leads to MSSM with

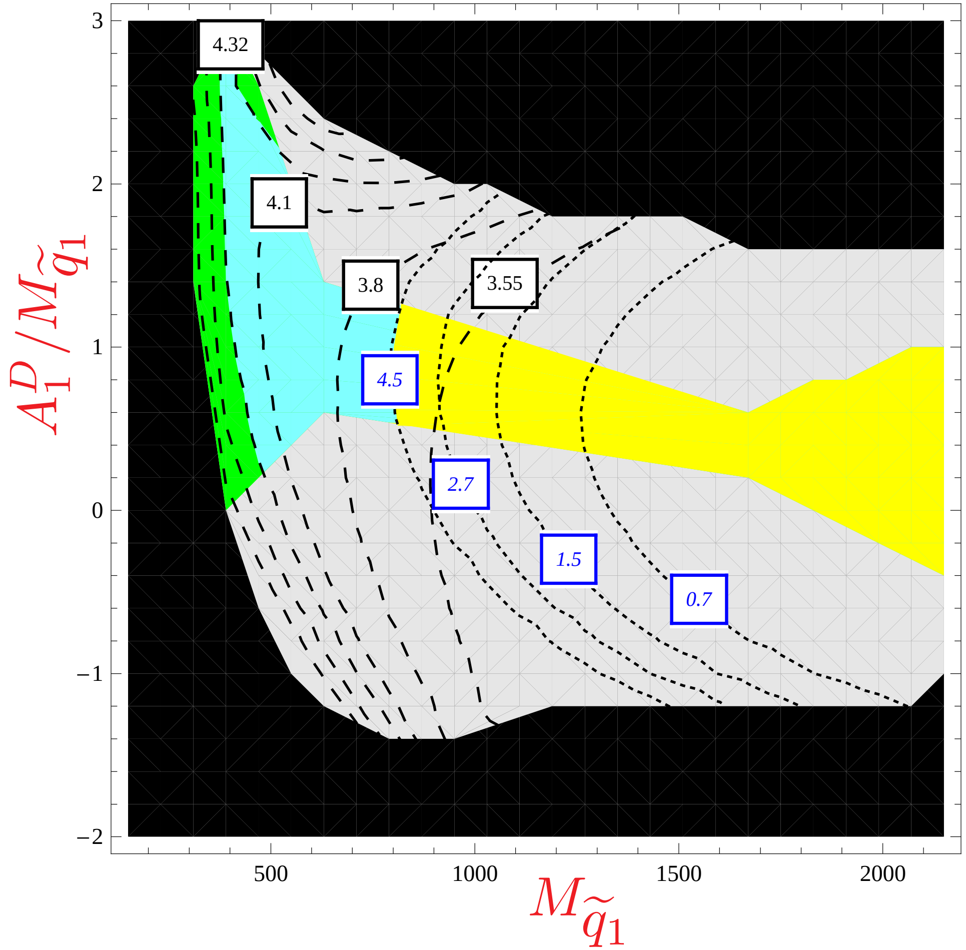
1. new loop-induced $b_R \rightarrow s_R$ and $b_L \rightarrow s_R$ transitions, while all other FCNC transitions are CKM-like,

2. all MSSM masses and couplings fixed in terms of a few GUT parameters.

The (CMM) model is a well-motivated falsifiable version of the MSSM without minimal flavour violation (MFV).
It puts the largest effects into $b_R \to s_R$ transitions, where data leave the most room for new physics.

Constraints from $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing, $\tau \to \mu\gamma$ and $b \to s\gamma$ on $M_{\widetilde{q}_1}$ and $A_1^D/M_{\widetilde{q}_1}$

Contour plot for $M_{\tilde{g}} = 350\,\mathrm{GeV}$, $\arg\mu = 0$:



Black: negative soft masses^2

Green: excluded by $\tau \to \mu\gamma$ and $b \to s\gamma$

Blue: excluded by $\tau \to \mu\gamma$

Gray: excluded by $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing

Yellow: allowed

dashed lines: $10^4 \cdot Br(b \to s\gamma)$; dotted lines: $10^8 \cdot Br(\tau \to \mu\gamma)$.

S. Jäger, M. Knopf, W. Martens, UN, C. Scherrer, S. Wiesenfeldt

Impact of the experimental lower bound on the lightest Higgs mass,
$M_{h^0} > 114$ GeV:

Small values of $\tan\beta$ are excluded, need $\tan\beta \gtrsim 6$.

$\Rightarrow$ Top-Yukawa coupling y_t below its fixed-point.
y_t small between M_{GUT} and M_{Planck}.
Most FCNC effects suppressed below present experimental uncertainites; effect most visible in $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing.

4. Summary and Outlook

- Sizable effects of new physics are possible in $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing.
- In GUT models one can connect quark flavor physics with lepton flavor physics and collider physics. The large atmospheric neutrino mixing angle can induce large $b_R \to s_R$ transitions.
- In the CMM model we can easily explain the hints of new physics in the CDF and DØ data on the $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing phase ϕ_s^Δ without conflict with $b \to s\gamma$ and $\tau \to \mu\gamma$.
- Tevatron experiments could try to eliminate the two-fold ambiguity in ϕ_s^Δ by studying $B_s(t) \to D_s^\mp K^\pm$. S. Nandi, UN

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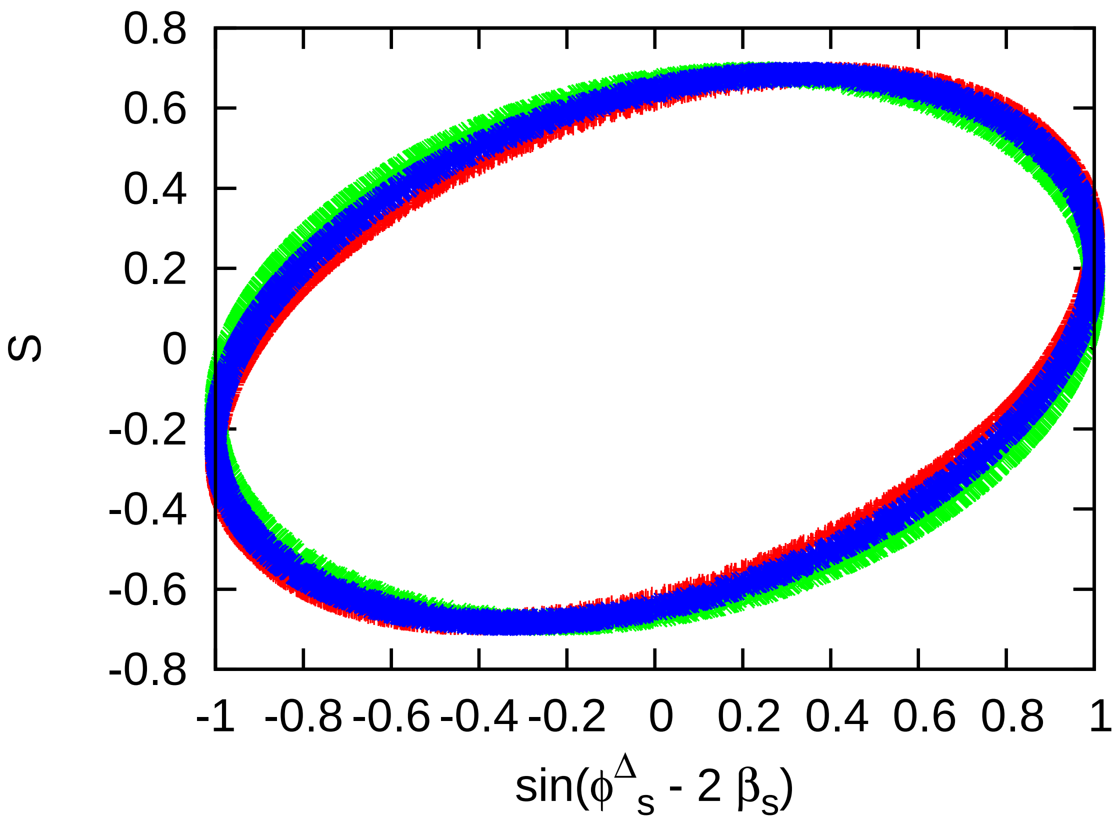
Even with poor statistics a measurement of $B_s(t) \to D_s^{\mp} K^{\pm}$ should permit the resolution of today's discrete ambiguity in ϕ_s^{Δ}. The coefficient S of the $\sin(\Delta m_s t)$ term in $B_s(t) \to D_s^{\mp} K^{\pm}$ is:



Upper branch: $\cos \phi_s^{\Delta} > 0$

Lower branch: $\cos \phi_s^{\Delta} < 0$.

Soumitra Nandi, UN